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An adaptive temperature control law for a solar furnace

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ABSTRACT

This paper describes the development of an adaptive control law based on the exact feedback linearization and Lyapunov adaptation of the process dynamics applied to a solar furnace. The algorithm resulting from these underlying design principles is approximated in order to relate it with an adaptive PI controller with feedforward. The controller is tested on a 6 kW solar furnace model that represents a plant installed at the Odeillo Processes Materials and Solar Energy Laboratory (Oriental Pyrenees in the South of France). The adaptive features allow to tackle the problems posed by knowledge uncertainty about furnace dynamics. It is concluded that the specifications related to material testing are met.

1. Introduction

Nowadays there is a huge concern about the use of energy sources that contribute to the climatic change problem. To mitigate the problem, the exploitation of solar energy has been considered in several ways, by converting it to thermal and electric energy, using either thermal solar fields or photovoltaic systems/panels. Solar energy is also used in other fields such as the synthesis of high-temperature materials, and in material testing (Fernandes et al., 2006), thermal stress (Fernandes, Amaral, Rosa, & Shohoji, 2000), or to recreate the conditions of the reentry of spacecrafts in Earth's atmosphere. It is worth to mention that the development of the Odeillo solar plant was motivated by research on materials to be used in space rockets, guided missiles and nuclear plants (Boyle, 1996), thereby avoiding the problems of testing them with direct radioactive elements. All those applications of solar energy systems pose interesting problems from the automatic control point of view (Berenguel, Camacho, Garcia-Martin, & Rubio, 1999; Lemos, 2006), such as the presence of disturbances, non-linearities, and variable delays.

Solar furnaces concentrate solar energy in a limited area, around the focus of a concentration mirror, or Fresnel lens, and allow to attain high temperatures. Despite its interest, there is a scarce number of references on the specific topic of solar furnace control. A major exception is the work of Berenguel et al. (1999) where modeling and control of a 20 kW furnace located at Plataforma Solar de Almeria (southern Spain) is presented. The work reported therein includes several types of PID with gain scheduling and a self-tuning controller. In Paradkar and Feliachi (2002) a controller is proposed to compensate disturbances in a solar furnace, and in Lacasa, Berenguel, and Yebra (2006) a controller based in fuzzy logic is evaluated in a solar furnace for copper sintering. In Garcia-Gabin, Zambrano, and Camacho (2009) a sliding mode predictive controller is evaluated and applied to a solar air conditioning plant, and in Kojima, Taniwaki, and Okiami (2008) the problem of positioning a flexible solar array is addressed. In Costa et al. (2008a) experimental results are described with a PI for temperature control in the same furnace considered here.

In this paper the exact feedback linearization method together with Lyapunov adaptation (Slotine & Li, 1991) is used to design an adaptive controller for controlling the temperature of a sample in a solar furnace (Costa et al., 2008b). The prototype is the 6 kW solar furnace of Odeillo solar complex. In addition to the algorithm yielded by the direct application of these techniques, a modified version is also presented. This has the advantage of having a structure that is comparable to an adaptive PI controller with feedforward, thereby rendering the commissioning easier.

The contributions of this paper consist in the application of the above-mentioned algorithms, in order to develop a new modified structure, and its demonstration by simulation in a realistic furnace model.

This paper is organized as follows. Section 2 describes the solar furnace plant, in particular the thermal model subsystem. Section 3 describes the design of the adaptive controller using the exact linearization method. Simulation results are shown and discussed. Section 4 describes the modification of the adaptive controller and results are presented. Section 5 presents the stability analysis of the closed loop system with the modified adaptive controller. Section 6 draws conclusions.

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2. Plant description

The plant to control is the 6 kW solar furnace of the Odeillo Process Materials and Solar Energy Laboratory. It is made of four subsystems: the heliostat system, the parabolic mirror and its flux distribution, the shutter system and the temperature control system.

2.1. Heliostat

The heliostat, Fig. 1, operates in closed-loop control and follows the movement of the Sun with accuracy, in such a way that the parabolic concentrator located at the top of the building, inside the laboratory, Fig. 1, receives the Sun beam always along the same direction. This allows the focus to be in the same place during operation of the solar furnace. With the heliostat operating in closed-loop control, it may be assumed that the tracking of the Sun's position is perfect and there is no need to consider the effects of heliostat's dynamics in the temperature of the sample. The closed-loop mode is selected whenever the measured direct Sun's power is higher that $300\,W/m^2$. Below $300\,W/m^2$ the furnace does not operate.

The solar direct radiation is not constant but can exhibit some changes due to air moisture, dust, clouds, and during the day and season. Fig. 2 shows two data records taken in (2003/05/03) and (2006/05/25). The quantity of energy reflected by the heliostat's mirror (Fig. 1) depends on its area and also on the cleanliness of the mirror, which will decrease with time due to dust deposition. Depending on time and dust level, the reflected power can vary from 85% to 90% of the available Sun's power.

2.2. Parabolic concentrator

The parabolic concentrator is built with small hexagonal mirrors that direct the solar energy to the location where the sample to be tested is placed. The maximum available power at the focus is 6 kW. The position of the sample can be adjusted by manually commanding the position of the supporting arm, Fig. 3, that can be moved in the North–South, West–East and up–down directions using the operating console.

Assuming that the shutter is not present, the flux on the focus is approximated by a Gaussian function. The focus has a diameter of 6 cm, and receives 95% of the power concentrated by the parabolic mirror. The flux inside the area of the focus is not uniform but, for practical purposes, it may be considered that a circle with radius of 2.5 cm centered at the focus receives a uniform flux. The size of the focus can be changed by moving the supporting arm in the up–down direction.

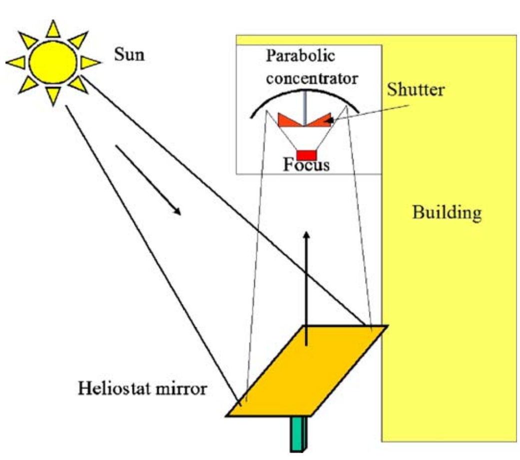

Fig. 1. Schematic of the Odeillo 6 kW solar furnace.

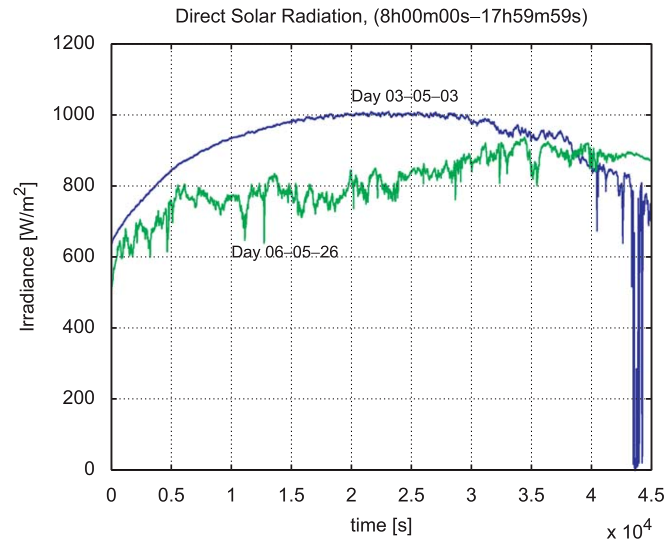

Fig. 2. Direct solar radiation evolution with time. Examples show disturbances due to moisture in air, dust and clouds.

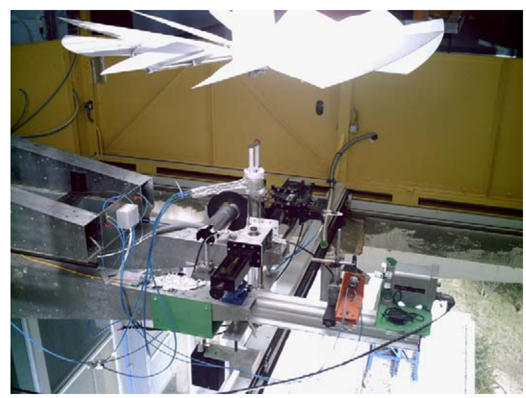

Fig. 3. Shutter of the 6 kW solar furnace (top). Test tube in the focus with a SiC sample (center).

2.3. Shutter

The shutter (Fig. 3) is made of 10 moveable aluminum blades with a thickness of 2.0 mm. It has a circular like shape with a radius of 0.5 m. The blades are moved by a brushless motor (from the Parvex manufacturer) using a gear mechanism. The subsystem motor-blades is controlled with a Digivex controller, which receives positional commands (reference signal) to position the blades. The commands can be sent using the operating console or by a personal computer through the data acquisition system InstruNet.

The shutter of the solar furnace is able to quickly change the incident power on the sample, an important factor for the purpose of temperature control. The physical aspect of the shutter, location, size and material were selected in order to yield a fast time response. In the shutter subsystem there are two aspects to be considered: the static function $s_{fs}(.)$ that describes the steady-state relation between the power available before the shutter and the power available at the focus, and the dynamics of the shutter. The static function $s_{fs}(.)$ depends on θ, the angle of the shutter, and θ_0 the minimal angle value below which there is no power at the